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(71)(72) Applicant and Inventor: FARNSWORTH, David, F. [US/US]; 1934 S.W. Stringtown Road, Forest Grove, OR 97116 (US).

(74) Agents: BIRDWELL, William, A. et al.; William A. Birdwell & Associates, Suite 1260, 900 S.W. Fifth Avenue, Portland, OR 97204 (US).

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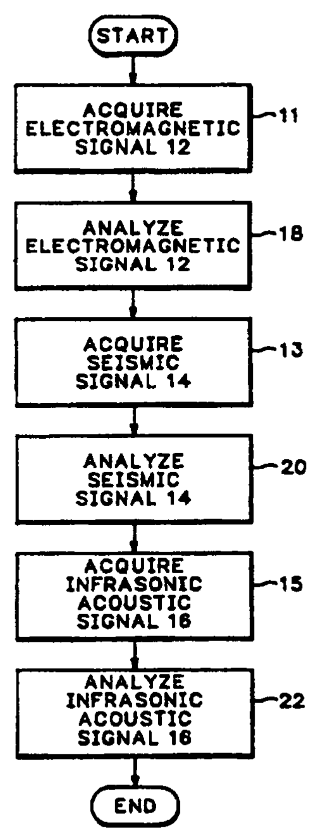
(54) Title: METHOD FOR FORECASTING AN EARTHQUAKE FROM PRECUSOR SIGNALS

(57) Abstract

A method for forecasting an earthquake from precursor signals by employing characteristic first electromagnetic signals (12), second, seismically induced electromagnetic signals (14), seismically induced mechanical signals, and infrasonic acoustic signals (16) which have been observed to precede an earthquake. From a first electromagnetic signal, a magnitude, depth beneath the surface of the earth, distance, direction, latitude, longitude, and first and second forecasts of the time of occurrence of the impending earthquake may be derived (18). From a second, seismically induced electromagnetic signal and the mechanical signal, third and fourth forecasts of the time of occurrence of an impeding earthquake determined from the analysis above, a magnitude, depth beneath the surface of the earth and fourth and fifth forecasts of the time of occurrence of the impending earthquake may be derived (22). The forecasts of time available from the above analyses range from up to five weeks to substantially within one hour in advance of the earthquake.



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METHOD FOR FORECASTING AN EARTHQUAKE FROM PRECURSOR SIGNALS

Background of the Invention

This invention relates to forecasting the magnitude, location, depth and timing of an earthquake by the acquisition and interpretation of extremely low frequency acoustic, seismic and electromagnetic signals which precede it.

The importance of an accurate method of forecast is manifest--the annual number of deaths due to earthquake has averaged about 17,000 throughout this century. Forecasting may allow people to take life-saving precautionary measures. But, Cinna Lomnitz, in his 1994 book, "Fundamentals of Earthquake Prediction," opines that "earthquake prediction . . . in the sense of forecasting the date, location, and magnitude of an earthquake" is simply not yet feasible today. Earthquake forecasting to date has been largely unsuccessful, apparently because the theory of plate tectonics is incomplete, and because empirical relationships between measurable phenomena and subsequent earthquake activity that may reliably forecast that activity have not been discovered.

Using the well known "hypothesis of characteristic earthquakes," earthquakes along the San Andreas Fault in California have been forecast statistically, by noting the time periods between previous earthquakes and assuming a characteristic time and location for the build-up and release of strain energy. The 1989 Loma Prieta earthquake was claimed to have been, to some extent, "predicted" by this means, however to many geologists, the actual location of and mechanism for its occurrence undermined the deterministic hypothesis supporting the method. In addition, even if earthquake processes are deterministic, statistical uncertainty remains in amounts sounding the death knell for forecasting that would allow for the taking of temporary precautionary measures, e.g., evacuation. See, Cinna Lomnitz, Fundamentals of Earthquake Prediction, 36-41, (1994).

Another method of forecasting is to measure accumulated ground strain as an indication of impending energy release due to the inexorable sliding or subductive motion of the underlying plates. In order for this indicator to give more than a gross estimate of time, location, or even magnitude of an eventual earthquake, many details about the physics of the plates and the convective mantle processes which drive them, as well as the local physical properties of the crust, would need to be better known. See, e.g., Ibid. at 180-86.

Another method of forecasting is to simply map the locations and energies of past earthquakes to determine a probability of future occurrence. An obvious difficulty with this method is that it neglects completely the time variable. Further, such a seismicity map of California made six years in advance of two very damaging earthquakes in Parkfield and San Fernando showed for those locations saddlepoints of seismic energy, implying, with devastating inaccuracy, that these were two of the least hazardous locations along the San Andreas Fault. Ibid. at 105.

Animal behavior, especially that of migrating or swarming animals such as birds, bees and fish, has long been thought to be a precursor to earthquake activity. However, attempts to interpret and even to describe the precursive behavior unambiguously, have been frustrating. A fundamental problem is that the range of animal behavior can be quite broad, and specific behavior with respect to earthquake activity, which is a relatively rare occurrence in the life of one animal, is difficult to demonstrate.

After the 1989 Loma Prieta earthquake, it was discovered that electromagnetic radiative signals in the frequency range of .01 Hz to .02 Hz increased dramatically prior thereto, using an instrument that had been installed just four months prior to the quake. No subsequent bursts have been recorded, suggesting that the bursts may have been precursors, but the evidence is considered by scientists to be inconclusive, and no reliable method of earthquake forecasting relying on these signals has previously been determined. Ibid. at 138.

Haroun Tazieff, in his 1989 book, "Earthquake Prediction," discusses a method of forecasting known in the art as the "VAN method," developed by three Greek scientists whose initials form the acronym. The method consists of continuously recording telluric currents using a network of monitoring stations which cover a particular region. These currents move in sheets of electricity, in the soil, close to the surface of the earth. By using two buried electrodes, one oriented north-south and the other east-west, a station is believed to acquire a SES (seismic electrical signal) that "always seems to precede an earthquake." See, Haroun Tazieff, Earthquake Prediction, 67 (1989). The intensity of the signal is thought to be proportional to the predicted magnitude of the earthquake, and inversely proportional to its distance from the station. The SES signal is believed to manifest as a sudden deviation, either negative or positive, in the otherwise relatively stable value of telluric current. These deviations are on the order of millivolts, and are known to be confounded by noise for less energetic or more distant quakes. Because, by this method, only the distance to the forecasted earthquake may be determined, at least three stations, separated by appropriate distances, are necessary to triangulate the location of a forecasted earthquake. An exception results from a station's having received an SES from a particular area, which is thought to calibrate that station to earthquakes from that region, so that only one station is thought to be necessary to monitor activity at that location.

There are many physical measurements that could be made upon the earth with a hope of correlating to impending seismic activity. For example, changes in deep water levels, sound wave velocity, emissions of gas, electrical resistivity and magnetic field have all been proposed as potentially useful indicators. But all of these attempts to date have failed to provide accurate, repeatable forecasting at specific locations and times. The VAN method is thought by its proponents to provide accurate, repeatable

forecasting; however, it generally requires the use of at least three monitoring stations, widely dispersed enough to accurately triangulate, yet close enough to the site to receive signals distinguishable from noise. Further, the method is not thought to give a precise forecast of time, its resolution being no better than about ten days. Finally, it is reasonable to suspect that the method, since it has been known in the art for more than five years and earthquake forecasting is still not available to the public, is not as robust as has been thought. Since there can be no doubt of sufficient motive to employ immediately any reasonably cost efficient and workable technique to minimize the devastating effects of earthquakes, the absence of widespread use of this method renders its capabilities doubtful.

Accordingly, there is a need for a novel method for reliably, precisely and cost efficiently forecasting seismic activity, particular serious seismic activity that may result in injury or death.

Summary of the Invention

The present invention provides a method for forecasting an earthquake from precursor signals which solves the aforementioned problems and meets the aforementioned need by employing characteristic first electromagnetic, seismically induced second electromagnetic, seismically induced mechanical, and infrasonic acoustic signals which have been observed to precede an earthquake. The method for forecasting an earthquake according to the present invention comprises measuring and interpreting four kinds of precursive signals: infrasonic first electromagnetic signals in the frequency range of zero to 10 Hz, seismically induced second electromagnetic signals in the frequency range zero to one Hz, seismically induced mechanical signals in the

same frequency range, and infrasonic acoustic waves in the frequency range of zero to 10 Hz travelling in the atmosphere.

Naturally occurring first electromagnetic signals in the range of zero to 10 Hz are found normally to exhibit a relatively flat baseline which includes a characteristic noise. However, distinctive first electromagnetic signals indicative of impending earthquake activity are received up to five weeks in advance of the earthquake. These signals arrive serially in time, each signal exhibiting a characteristic fast transition (either positive or negative) from the baseline, followed by a first peak and a second peak, for quakes that are sufficiently distant from the location of signal receipt, within a few seconds, followed further by a substantially exponential decay toward a baseline, and followed still further by a steadily increasing variation from the baseline referred to herein as ringing. The time of first receipt of the signals provides a first time forecast of the earthquake. The time of cessation of the signals provides a second time forecast of the earthquake. The time between the first peak and the second peak (when available) is relatable to the distance to an impending earthquake, and the time from the first transition of the signal to its substantial decay is relatable to the depth of the impending earthquake. The amplitude of the signal is relatable to the magnitude of the impending earthquake. The ringing is observed to increase over time and, when Fourier or otherwise spectrally transformed to reveal frequency content, reveals a pronounced spectral peak which is observed over time to grow steadily in amplitude, centered at a frequency which is relatable to the latitude of the impending earthquake, and having a maximum amplitude which is relatable to the magnitude of the impending earthquake. The ringing, when analyzed for phase content provides a phase fluctuation, at the center frequency of the spectral peak, which is relatable to the longitude of the impending earthquake.

A substantial increase in a second, seismically induced electromagnetic signal, received from an electromagnetic transducer and representative of naturally occurring seismic motion, sensed at the same site, that is either substantially coincident with or follows the first electromagnetic signals within approximately three weeks, increases the probability that the first electromagnetic signals correlate to an earthquake that will actually materialize rather than be dissipated by alternative modes of energy release. Further, the time of first receipt of the seismically induced second electromagnetic signal provides a third forecast of the time of the earthquake, and the time of cessation of the signal provides a fourth forecast of the time of the earthquake.

The same information is available from a transducer, buried in the earth substantially 500 miles or less for a transducer having 10V/g, from the site of the impending earthquake, adapted to convert mechanical motion to electrical signals, which produces an electrical signal in response to a seismically induced mechanical signal, but at an increased resolution.

Infrasonic acoustic waves measured at the site of the impending earthquake located by analysis of the electromagnetic signals provide a fifth and sixth forecast of the time of the earthquake.

Therefore, it is a principle object of the present invention to provide a novel and improved method for forecasting of an earthquake.

It is a further object of the present invention to provide such a method that is reliable, precise and cost-efficient.

It is still a further object of the present invention to provide such a method that minimizes the number of continuous monitoring stations required.

It is another object of the present invention to provide such a method to forecast an impending earthquake by sensing a precursive electromagnetic signal.

It is yet another object of the present invention to provide such a method to forecast an impending earthquake by sensing a precursive seismic signal.

It is still another object of the present invention to provide such a method to forecast an impending earthquake by sensing a precursive atmospheric infrasonic acoustic signal.

It is another object of the present invention to provide such a method which forecasts the magnitude of an impending earthquake.

It is yet another object of the present invention to provide such a method which forecasts the distance to the site of an impending earthquake.

It is still another object of the present invention to provide such a method which forecasts the depth of an impending earthquake.

It is a further object of the present invention to provide such a method which forecasts the latitude of the site of an impending earthquake.

It is yet a further object of the present invention to provide such a method which forecasts the longitude of the site of an impending earthquake.

It is still a further object of the present invention to provide such a method which forecasts the time of surface occurrence of an impending earthquake.

The foregoing and other objects, features and advantages of the invention will be more readily understood upon consideration of the following detailed description of the invention, taken in conjunction with the accompanying drawings.

Brief Description of the Drawings

Figure 1 is a flow diagram showing an overview of a method for determining the location, magnitude and timing of an impending earthquake according to the present invention.

Figure 2 is an exemplary representation of the amplitude in millivolts of a characteristic electromagnetic signal precursive of an earthquake measured with respect to time according to the present invention.

Figure 3 is a representation of the amplitude in microvolts of the frequency spectrum of a first portion of the electromagnetic signal of Figure 1, according to the present invention

Figure 4 is a representation of the amplitude in microvolts of the frequency spectrum of a second portion of the electromagnetic signal of Figure 1, according to the present invention.

Figure 5 is an exemplary representation of the phase of the second portion of the electromagnetic signal of Figure 4 as a function of frequency, according to the present invention.

Figure 6 is a flow diagram of a preferred embodiment of a method according to the present invention, to verify the likelihood of an impending earthquake and to provide a first time forecast of the impending earthquake.

Figure 7 is an exemplary representation of the development, over time, of the magnitude of a seismic signal, utilized in conjunction with the method of Figure 6.

Figure 8 is a flow diagram of a preferred embodiment of a method according to the present invention, to provide a second time forecast of an impending earthquake.

Figure 9 is an exemplary representation of the development, over time, of the magnitude of an infrasonic signal, utilized in the method of Figure 8.

Detailed Description of a Preferred Embodiment

Referring to Figure 1, a method 10 for forecasting an impending earthquake according to the present invention comprises acquiring a first electromagnetic signal 12 (Figure 2), at step 11, a pair of seismic signals 14 (Figure 7), at step 13, and an infrasonic acoustic atmospheric signal 16 (Figure 9), at 15. The seismic signals 14 include a second, seismically induced electromagnetic signal portion and a seismically induced mechanical signal portion. Both portions carry substantially the same information and will be treated alike for purposes of analysis herein. Each acquisition step 12, 14 and 16 is followed by a step 18, 20

and 22, respectively, wherein the signal received in the preceding step is analyzed to provide information about the impending earthquake. The impending earthquake will be defined herein as an anticipated shaking of the ground at the surface of the earth in response to underlying seismic activity which produces these precursive signals. The signals 12, 14 and 16 are all preferably acquired by suitable receiving apparatus (not shown). Suitable receiving apparatus for the signal 12 include that described in Farnsworth, et. al., patent application No. PCT/US94/02630, hereinafter incorporated by reference in its entirety, where adapted to eliminate through filtration frequency components of the signal 12 above substantially 10 Hz. Suitable receiving apparatus for the signal 14 include that described in Farnsworth, et. al., patent application No. PCT/US94/02626, hereinafter incorporated by reference in its entirety, for the seismically induced electromagnetic signal portion of the signal 14, and a pair of horizontally and vertically disposed accelerometers providing at least ten volts/g, where "g" is the acceleration of gravity, such as marketed by PCB Electronics of Depew, New York as model No. 393B12, for the seismically induced mechanical signal portion of the signal 14. Both sets of apparatus are adapted to respond to frequency components of the signal 14 below substantially one Hz. Suitable receiving apparatus for the signal 16 are adapted to receive signals in the range of zero to 10 Hz, and preferably include a digital signal analyzer and an infrasonic microphone having a sensitivity of about 0.01 Pascals or better.

The first electromagnetic signal 12 is preferably received from the electrical power grid and monitored continuously; however, it may be obtained with other suitable antennae and sampled between suitable time periods without departing from the principles of the invention.

The first electromagnetic signal 12 is analyzed according to step 18 to provide the location, magnitude and a first and second time forecast of an impending earthquake. The seismic signal 14 is determined according to step 20 to

verify the materialization of the impending earthquake and to provide a third and fourth time forecast of the impending earthquake. The infrasonic signal 16 is analyzed according to step 22 to provide a fifth and sixth time forecast of the impending earthquake, and may also be utilized to provide estimated magnitude and depth of the impending earthquake.

Referring to Figure 2, the step 11 of acquiring the first electromagnetic signal 12 includes locating a series of characteristic pulses 24 (only one characteristic pulse 24 is shown in Figure 2). It has been found that the series of characteristic pulses 24 are indicative of a likelihood of an impending earthquake somewhere in the world. The electromagnetic signal 12 is preferably acquired by a digital signal analyzer which provides both time domain and frequency domain information and is reported in the time domain as a voltage amplitude 26, typically in millivolts, and a time 28, typically in seconds, for resolving beneficially the characteristic pulse 24. The pulse 24 includes a fast transition 30, a first peak 32, a second peak 34, a decay 36 and a ringing 38.

The fast transition 30 is shown in Figure 2 as a rise in amplitude, i.e. a positive transition, however it may be a negative going change in amplitude, i.e. a negative transition. Accordingly, for purposes herein, a reduction in the absolute value of the amplitude is referred to as a fall and an increase in the absolute value of the amplitude is referred to as a rise. Whether a pulse 24 rises or falls has been found to depend, at any given time, on the hemisphere of the earth in which the impending earthquake originates. Whether a pulse rises or falls determines whether the decay 36 falls or rises respectively toward the baseline.

The step 18 of analyzing the first electromagnetic signal comprises determining a time 39 in seconds between the first peak 32 and the second peak 34. It has been found that the time 39 is dependent upon the distance to the impending earthquake apparently due to dispersive broadening of the pulse 24 that occurs during the propagation time of

the electromagnetic signal 12 within and along the earth. When corrected for this broadening, the time 39 has been found to be proportional to the distance, along the surface of the earth, to the site of the impending earthquake. Consequently, the distance along the surface of the earth to the impending earthquake is determined by multiplying the time 39 by an appropriate predetermined constant. This constant has been found to vary between substantially 100 miles/second and 2400 miles/second, depending substantially proportionally upon distance, with greater distances associated with greater speeds, when the earthquake arises within the United States and the antennae is the United States power grid. Further, the second peak 34 may be arbitrarily close in time to the first peak 32, for near field earthquakes. Consequently, for filtering of the electromagnetic signal of 10 Hz, earthquakes nearer to the site of detection of the electromagnetic signal 12 than substantially 10 to 240 miles, under the conditions described above, will not be evidenced by a second peak 34, and therefore no distance forecast is provided by the aforedescribed analysis.

The step 18 of analyzing the electromagnetic signal further comprises determining a pulse width 43 between the time of initiation 44 of the fast transition 30 (which for purposes herein, is considered equal to the time of initiation of the first peak 32), and the time of termination 46 of a 90% decay of the decay 36. It has been found that the time 46 is also dependent on the distance to the impending earthquake, apparently due to dispersive broadening of the pulse 24 that occurs during the propagation time of the electromagnetic signal 12 within and along the earth. When corrected for this broadening, the pulse width 43 has been found to be proportional to the depth, below the surface of the earth, of the impending earthquake. Consequently, the depth of the impending earthquake is forecasted by multiplying the pulse width 43 by a predetermined constant calculated from empirical data.

The step 18 still further comprises determining a voltage amplitude 48 of the first peak 32. The voltage amplitude 48 has been found to be proportional to the magnitude of the impending earthquake. The amplitude is dependent on, inter alia, the sensitivity of the monitoring equipment and attenuation of the signal 12 by the antennae. Consequently, the magnitude of the impending earthquake is forecasted by multiplying the amplitude 48 by a predetermined constant calculated from empirical data.

A time of first initiation (not shown) of the first electromagnetic signal 12 has been found to occur substantially five weeks or less in advance of the occurrence of the earthquake, providing a first time forecast of the earthquake. The time of first initiation is the first time at which the first electromagnetic signal 12 is discernible. A time of cessation (also not shown) of the first electromagnetic signal has been found to occur substantially one day in advance of the occurrence of the earthquake, providing a second time forecast of the earthquake. The time of cessation is the last time at which the electromagnetic signal 12 is discernible. It has been found that the electromagnetic signal 12 substantially abruptly extinguishes itself at the time of cessation, as compared to its rate of change following its initiation.

Referring to Figures 2 and 3, the step 18 still further comprises operating upon the electromagnetic signal 12 mathematically so that it is projected onto sinusoidal basis functions, as in a Fourier transform, to provide a frequency spectrum 50. This preferably is done using the aforementioned digital signal analyzer. The frequency spectrum 50 is reported as a voltage amplitude 52 and a frequency 54. In a preferred embodiment, the voltage amplitude 52 is reported in microvolts and the frequency 54 is reported in the range of zero to 10 Hz. The frequency spectrum 50 comprises spectral peaks 56 defined by frequencies 58 which have been found to be indicative of the latitude of earthquake sites thus monitored. When operated upon prior to the ringing 38, peaks 56 of the

electromagnetic signal 12, when roughly equal to one another in amplitude 52, are not indicative of an impending earthquake, consequently the peaks 56 are non-indicative peaks.

However, referring to Figures 2 and 4, when operating upon the electromagnetic signal 12 at the time during the ringing 38 in the manner described above, to provide a frequency spectrum 50, also as above, some of the spectral peaks 56 are found to increase in amplitude 52. When the peaks 56 increase substantially together, there is again no indication of an impending earthquake at the latitudes corresponding to those frequencies 58, and consequently the peaks 56 remain non-indicative peaks. However, an indicative peak 60 will be noticed to increase much more than the non-indicative peaks 56. As the series of pulses 24 (Figure 1) become closer in time 28 (Figure 1), the indicative peak 60 will be seen to rise further above the non-indicative peaks 56. The frequency 62 about which an indicative peak 60 is centered has been found to be relatable to the latitude of the impending earthquake. The latitude at the rotational poles of the earth has been found to correspond substantially to 7.8 Hz, while the latitude at the equator of the earth has been found to correspond substantially to zero Hz, the dependence of frequency on latitude therebetween varying sigmoidally. The latitude of the impending earthquake is forecasted by relating the frequency 62 to a corresponding predetermined value of latitude. In a preferred embodiment, the latitude of the impending earthquake is forecasted by relating the frequency 62 to a predetermined value obtained from a look up table based an empirical data collected by monitoring over a period of time the electromagnetic signals associated with many earthquakes. The look-up table is preferably encoded for use by a computer.

The step 18 still further comprises determining the magnitude 64 of the indicative peak 60. The magnitude of the impending earthquake has been found to be proportional to the transcendental constant "e" raised to the power of

the amplitude 64. Consequently, the magnitude of the impending earthquake is forecasted by multiplying "e" raised to the power of the amplitude 64 by a predetermined constant calculated from empirical data. This method of forecasting the magnitude of the impending earthquake, with respect to the aforedescribed alternative based upon analysis of the pulse 24, is considered the preferred method.

Referring to Figure 5, the step 18 still further comprises operating upon the electromagnetic signal 12 to provide a phase versus frequency spectrum 65. The phase of signal 12 corresponding to the frequency 62 of the indicative peak 60 has been found to change with time. More specifically, it has been found that a magnitude 67 (which may be positive or negative) of the total phase fluctuation is proportional to the longitudinal difference in the location of the site of the impending earthquake and the location of the acquisition of the electromagnetic signal 12. Consequently, the longitudinal difference is forecasted by multiplying the magnitude 67 by a predetermined constant calculated from empirical data.

A longitudinal direction may be determined by measuring the phase difference between signals received by two respective antennas displaced from one another, to supplement the information provided by the phase versus frequency spectrum 65.

Alternatively, a longitudinal direction may be determined by employing a pair of directional antennae disposed to provide a set of basis vectors in the horizontal plane upon which a signal direction may be resolved, as will readily be appreciated by one of ordinary skill in the art.

Alternatively, after having acquired sufficient data over time, electromagnetic signals arising from known locations may be seen in time, frequency or phase representations to evidence a unique signature corresponding to that location, allowing for the ascertainment of earthquake location information without employing detailed measurements and mathematical relationships between those measurements and desired parameters.

Further, while the aforedescribed method provides the depth, latitude and longitude of, and distance to an impending earthquake, and therefore is capable of providing redundant surface location information even while only one monitoring station is employed, less information may be acquired and well known triangulation methods used to determine the surface location of the impending earthquake without departing from the principles of the invention.

It has been found that, in addition to the aforedescribed first electromagnetic signal 12, a second, seismically induced electromagnetic signal portion of the seismic signal 14, following in time the first electromagnetic signal 12, provides further information beneficial to the forecast of the earthquake. In addition, a seismically induced mechanical signal portion of the seismic signal 14 provides the same information as the seismically induced electromagnetic signal portion, however the seismically induced mechanical portion of the signal may be discernibly received only when monitoring the signal within substantially 500 miles, for a transducer providing 10V/g, from the site of the earthquake.

Referring, then, to Figures 6 and 7, either the second, seismically induced electromagnetic signal portion of the seismic signal 14 or the seismically induced mechanical signal portion of the seismic signal 14 may be first received at step 70.

A time of first initiation 72 of the seismic signal 14 is then determined at step 74 by noting the first time at which the seismic signal 14 is discernible above noise 79 (Figure 7). A time 76 is also determined at step 78 for the substantial rise of the indicative peak 60 (Figure 3). The time 72 is then compared with the time 76 at step 80. If the time 72 follows the time 76 by up to substantially three weeks, then the seismic signal 14 is verification of the materialization of the impending earthquake at the latitude determined from the frequency 62 of the indicative peak 60.

Further, the time 72 has been found to occur substantially two weeks or less in advance of the occurrence

of the earthquake, providing a third time forecast of the earthquake. Still further, a time of cessation (not shown) of the seismic signal 14 been found to occur substantially within one hour, i.e., a few minutes up to an hour in advance of the occurrence of the earthquake, providing a fourth time forecast of the earthquake. The time of cessation is the last time at which the seismic signal 14 is discernible. It has been found that the seismic signal 14 substantially abruptly extinguishes itself at the time of cessation, as compared to its rate of change following its initiation at time 72.

Referring to Figure 7, the seismic signal 14 has been found to exhibit a series of substantially sinusoidal wavelets 75 that are characteristic of an impending earthquake. The wavelets 75 associated with the impending earthquake have been found to develop over time so that their amplitude 77 is seen to grow steadily above the noise 79, as shown as an enveloping pattern 81 in Figure 7. This pattern may collapse at any time, by the amplitude 77 of subsequently received wavelets 75 decreasing to substantially zero, indicating that the impending earthquake will not materialize at the surface due to an alternative mode of energy release. However, a pattern 81 that persists at a sustained amplitude 83 over a sufficient period of time, found to be substantially one to two hours, followed by a sudden substantially complete cessation of amplitude 83, has been found indicative that the earthquake will materialize substantially within one hour, providing a short time forecast of the impending earthquake. The mechanically coupled signals 19 are considered to provide better resolution, and therefore to provide better forecasting information, than the electromagnetically coupled signals 17.

Referring to Figures 8 and 9, an impending earthquake site is determined at step 82 by analysis of the electromagnetic signals 12 as described above. Infrasonic acoustic signals 16 propagating in the atmosphere are then monitored at step 84 with suitable apparatus as described

above. A time of first receipt 86 of the infrasonic acoustic signals 16 is then determined at step 88, by noting the time at which the infrasonic acoustic signals 16 begin to exhibit a series of characteristic pulses 85 (Figure 9). The characteristic pulses 85 have been found to include features similar to those described for the electromagnetic signals 12 but without a second peak 34 (Figure 2) because the monitoring site will not be sufficiently distant from the earthquake as has been discussed above. It has been found that the time 86 of the first receipt of the characteristic pulses 85 indicates that the impending earthquake will follow in from one to three days, providing a fifth forecast of the time of occurrence of the earthquake at step 90.

It has also been found that infrasonic signals 16, over a relatively short period of time, change from having frequencies in a range of zero to 10 Hz to having frequencies in the range of 20 Hz, where they will not be excluded by a low pass filter of the monitoring apparatus. Consequently, the infrasonic signals 16 will be seen to cease at a characteristic time of cessae of cessation 88, and it has been found that from this time an impending earthquake is due within eight hours plus or minus one-half hour, providing a sixth forecast of the time of occurrence of the earthquake at step 94.

Further, because the characteristic pulses 85 of the infrasonic signals 16 include features similar to the characteristic pulses 24 of the electromagnetic signals 12 (Figure 2), information regarding magnitude, latitude, longitude and depth of the impending earthquake is ascertainable from these signals as well in the manner described for the electromagnetic signals 12, however in a preferred embodiment, in which the infrasonic signals are measured at or near the site of the impending earthquake, the latitude and longitude information contained therein is not presently considered useful.

It is to be recognized that, while a specific method has been described as the preferred embodiment of the

invention, other methods employing the principles of the invention could be utilized without departing therefrom. It is also to be recognized that, while these steps may be performed manually, they are preferably carried out by a digital processor appropriately programmed to identify the pertinent points on the signal waveforms and make the aforedescribed computations.

The terms and expressions which have been employed in the foregoing specification are used therein as terms of description and not of limitation, and there is no intention of the use of such terms and expressions of excluding equivalents of the features shown and described or portions thereof, it being recognized that the scope of the invention is defined and limited only by the claims which follow.

I claim:

1. A method for forecasting an earthquake, comprising:

receiving a naturally occurring electromagnetic signal at a known location on the earth;

determining whether, over a selected time interval, the amplitude of said electromagnetic signal changes more than a threshold amount, as a precursory indication of an earthquake;

where said amplitude changes by an amount greater than said threshold and thereafter decays, determining the maximum value of said amplitude; and

multiplying said maximum value by a predetermined value to determine the magnitude of said earthquake.

2. A method for forecasting an earthquake, comprising:

receiving a naturally occurring electromagnetic signal at a known location on the earth;

determining whether, over a selected time interval, the amplitude of said electromagnetic signal changes more than a threshold amount, as a precursory indication of an earthquake;

where said amplitude changes by an amount greater than said threshold amount and thereafter decays, identifying the time of occurrence of a resultant first peap2739Yfirst peak of said amplitude; and

where said amplitude thereafter falls and rises again a predetermined amount, identifying the time of occurrence of the resultant second peak of said amplitude;

determining the time between said first peak and said second peak; and

multiplying said time between said first peak and said second peak by a predetermined value to determine the distance over the surface of the earth from said known location to said earthquake.

3. A method for forecasting an earthquake, comprising:

receiving a naturally occurring electromagnetic signal at a known location on the earth;

determining whether, over a selected time interval, the amplitude of said electromagnetic signal changes more than a threshold amount, as a precursory indication of an earthquake;

where said amplitude changes by an amount greater than said threshold amount and thereafter decays, identifying the time of initiation of a resultant first peak of said amplitude;

where said amplitude thereafter decays by a predetermined amount, identifying the time of termination of the decay;

subtracting the time of initiation from the time of termination to form a pulse width; and

multiplying the pulse width by a predetermined value to determine the depth of said earthquake beneath the surface of the earth.

4. A method for forecasting an earthquake, comprising:

receiving a naturally occurring electromagnetic signal at a known location on the earth;

transforming said electromagnetic signal over a selected time interval to provide a frequency spectrum;

determining whether, during said selected time interval, the magnitude of a spectral peak is greater than the magnitude of any other part of said spectrum by a predetermined amount;

identifying the center frequency of said spectral peak, if determined; and

determining the latitude of said earthquake based upon a relationship to the center frequency.

5. The method of claim 4, wherein transforming said electromagnetic signal is by a Fourier transform.

6. The method of claim 4, wherein determining said latitude is by finding from a look-up table the latitude corresponding to said center frequency.

7. A method for forecasting an earthquake, comprising:

receiving a naturally occurring electromagnetic signal at a known location on the earth;

transforming said electromagnetic signal over a selected time interval to provide a frequency spectrum;

determining whether, during said selected time interval, the magnitude of a spectral peak is greater than the magnitude of any other part of said spectrum by a predetermined amount;

identifying the center frequency of said spectral peak, if determined; and

multiplying said magnitude by a predetermined value, to determine the magnitude of said earthquake.

8. A method for forecasting an earthquake, comprising:

receiving a naturally occurring electromagnetic signal at a known location on the earth;

transforming said electromagnetic signal over a selected time interval to provide a frequency spectrum;

determining whether, during said selected time interval, the magnitude of a spectral peak is greater than the magnitude of any other part of said spectrum by a predetermined amount;

identifying the center frequency of said spectral peak, if determined;

transforming said electromagnetic signal over a selected time interval to provide a phase-frequency relationship;

determining the amount of a phase fluctuation associated with the center frequency; and

multiplying the amount of said phase fluctuation by a predetermined value to determine the longitude of said earthquake.

9. A method for forecasting an earthquake, comprising:

receiving a naturally occurring electromagnetic signal at a known location on the earth from a first antenna;

determining whether, over a selected time interval, the amplitude of said electromagnetic signal changes more than a threshold amount, as a precursory indication of an earthquake;

receiving said naturally occurring electromagnetic signal from a second antenna;

determining a difference in the signals received from said first antenna and said second antenna; and

determining from said difference the direction of said earthquake from said known location.

10. The method of claim 9, wherein said second antenna is disposed a predetermined distance from said first antenna, and wherein said difference is a phase difference in said signals.

11. The method of claim 9, wherein said first antenna and said second antenna are directional antennae, wherein said second antenna is disposed a predetermined orientation with respect to said first antenna, and wherein said difference is a relative amplitude of said signals.

12. A method for forecasting an earthquake, comprising:

receiving a naturally occurring electromagnetic signal at a known location on the earth;

determining whether, over a selected time interval, the amplitude of said electromagnetic signal changes more than a threshold amount, as a precursory indication of an earthquake;

characterizing a signature of said electromagnetic signal and correlating said signature with empirical data to determine the location of said earthquake.

13. A method for forecasting an earthquake, comprising:

receiving a naturally occurring electromagnetic signal at a known location on the earth;

determining a time of initiation of said electromagnetic signal; and

determining a time of likely occurrence of said earthquake from said time of initiation by adding a predetermined period of time to said time of initiation.

14. The method of claim 13, wherein said predetermined period of time is substantially five weeks.

15. A method for forecasting an earthquake, comprising:

receiving a naturally occurring electromagnetic signal at a known location on the earth;

determining a time of cessation of said electromagnetic signal; and

determining a time of likely occurrence of said earthquake from said time of cessation, by adding a predetermined period of time to said time of cessation.

16. The method of claim 15, wherein said predetermined period of time is substantially one day.

17. A method for forecasting an earthquake, comprising:

receiving a transducer signal induced by a naturally occurring seismic signal at a known location on the earth;

determining whether said transducer signal exhibits a series of wavelets wherein said wavelets grow in amplitude over a predetermined period of time, to provide a precursory indication of said earthquake; and

determining a time of likely occurrence of said earthquake by identifying a time of initiation of said wavelets.

18. The method of claim 17, wherein determining said time of likely occurrence is by adding substantially two weeks to said time of initiation.

19. The method of claim 17, wherein said transducer transforms a first electrical signal to a second electrical signal.

20. The method of claim 17, wherein said transducer transforms a mechanical signal to an electrical signal.

21. A method for forecasting an earthquake, comprising:

receiving a transducer signal induced by a naturally occurring seismic signal at a known location on the earth;

determining whether said transducer signal exhibits a series of wavelets wherein said wavelets grow in amplitude over a predetermined period of time, to provide a precursory indication of said earthquake; and

determining a time of likely occurrence of said earthquake by identifying a time of cessation of said wavelets.

22. The method of claim 21, wherein determining said time of likely occurrence is by adding an amount of time substantially within one hour to said time of cessation.

23. The method of claim 21, wherein said transducer transforms a first electrical signal to a second electrical signal.

24. The method of claim 21, wherein said transducer transforms a mechanical signal to an electrical signal.

25. A method of forecasting an earthquake, comprising:

receiving a transducer signal induced by a naturally occurring seismic signal at a known location on the earth;

determining whether said transducer signal exhibits a series of wavelets wherein said wavelets grow in amplitude over a predetermined period of time, to provide a precursory indication of said earthquake;

determining a time of likely occurrence of said earthquake by identifying a time of initiation of said wavelets;

receiving a naturally occurring electromagnetic signal at a known location on the earth;

determining a time of initiation of said electromagnetic signal;

determining a time of likely occurrence of said earthquake from said time of initiation by adding a predetermined period of time to said time of initiation; and

comparing said time of initiation of said electromagnetic signal with said time of initiation of said wavelets wherein if said time of initiation of said wavelets wherein if said time of initiation of said electromagnetic signal precedes by substantially three weeks said time of initiation of said wavelets, said comparing provides verification of the forecast of said earthquake.

26. A method for forecasting an earthquake, comprising:

receiving a naturally occurring infrasonic acoustic signal at a known location on the earth;

determining a time of first receipt of said signal; and

determining a time of likely occurrence of said earthquake by adding a predetermined value to said time of first receipt of said signal.

27. The method of claim 26, wherein said predetermined value is substantially one to three days.

28. A method for forecasting an earthquake, comprising:

receiving a naturally occurring infrasonic acoustic signal at a known location on the earth;

determining a time of frequency shift of said signal to a substantially higher frequency; and

determining a time of likely occurrence of said earthquake by adding a predetermined value to said time of frequency shift.

29. The method of claim 28, wherein said predetermined value is substantially eight hours.

30. A method for forecasting an earthquake, comprising:

receiving a naturally occurring infrasonic acoustic signal at a known location on the earth;

identifying the time of initiation of a resultant first peak of said amplitude;

where said amplitude thereafter decays by a predetermined amount, identifying the time of termination therefor;

subtracting the time of initiation from the time of termination to form a pulse width; and

multiplying the pulse width by a predetermined value to determine the depth of said earthquake beneath the surface of the earth.

31. A method for forecasting an earthquake, comprising:

receiving a naturally occurring infrasonic acoustic signal at a known location on the earth;

determining a maximum amplitude of said signal and

multiplying said maximum amplitude by a predetermined value to determine the magnitude of said earthquake.

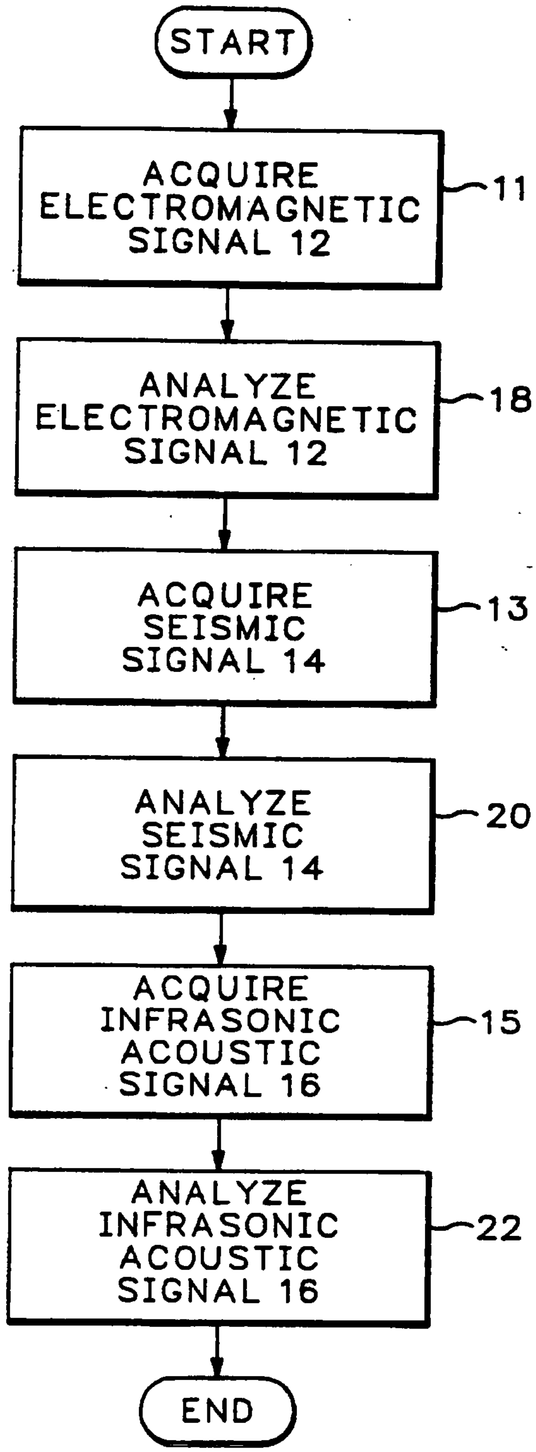
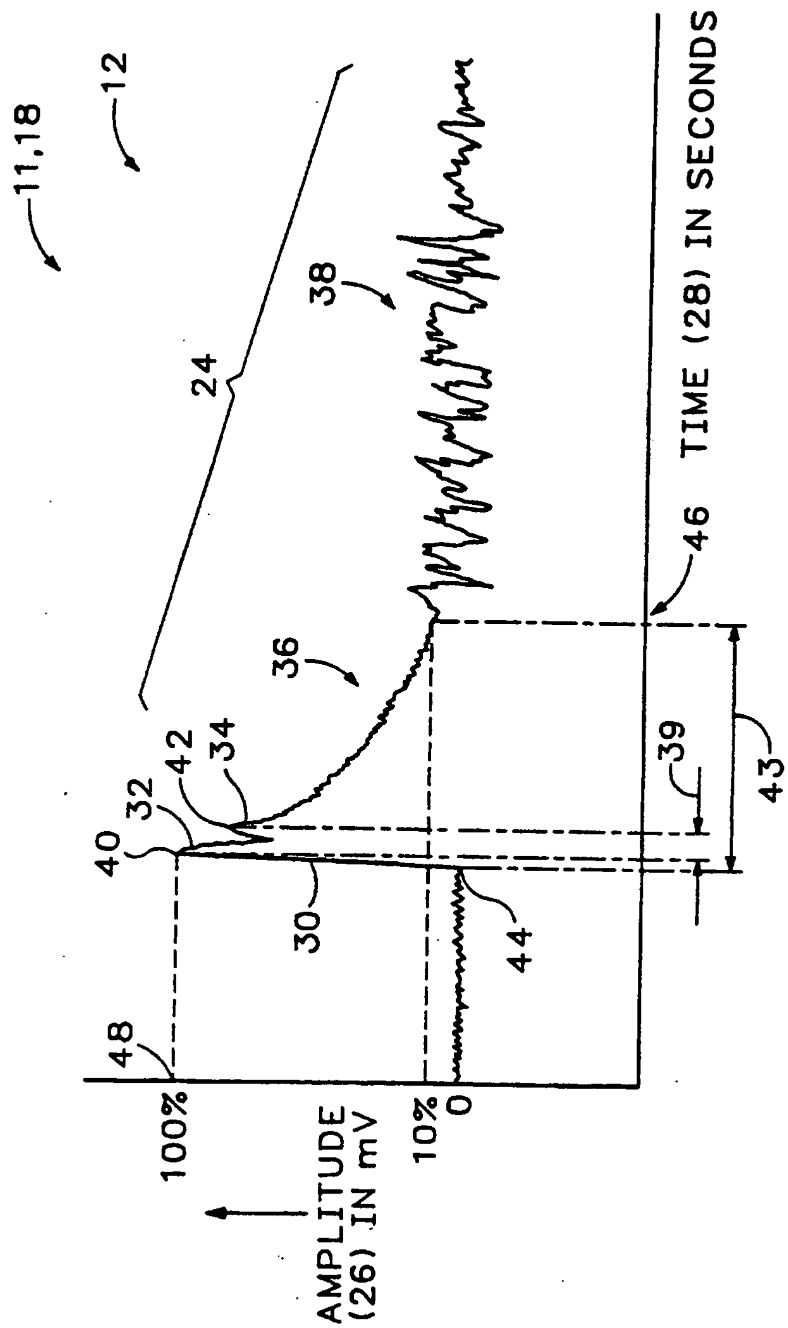

START
ACQUIRE ELECTROMAGNETIC SIGNAL 12
11
ANALYZE ELECTROMAGNETIC SIGNAL 12
18
ACQUIRE SEISMIC SIGNAL 14
13
ANALYZE SEISMIC SIGNAL 14
20
ACQUIRE INFRASONIC ACOUSTIC SIGNAL 16
15
ANALYZE INFRASONIC ACOUSTIC SIGNAL 16
22
END

Fig.1



11,18
12
24
38
36
40
32
42
34
39
43
30
44
46
48
100%
10%
0
AMPLITUDE (26) IN mV
TIME (28) IN SECONDS

Fig.2

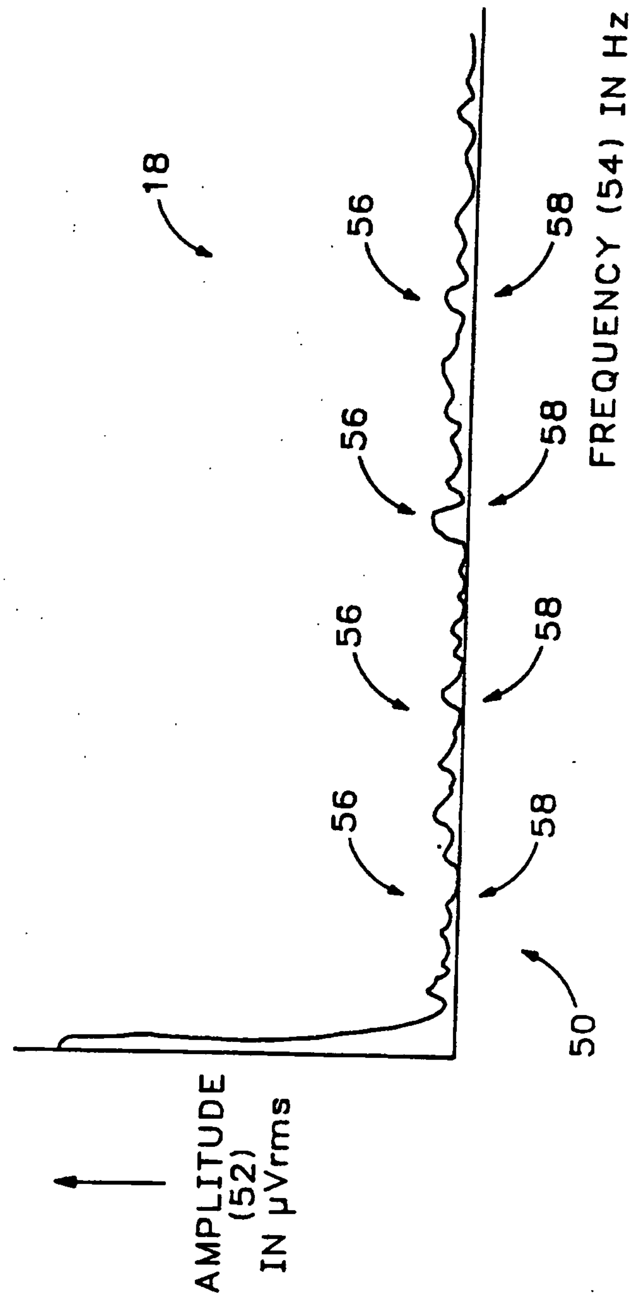

18
56
58
56
58
56
58
56
58
50
FREQUENCY (54) IN Hz
AMPLITUDE
(52)
IN μVrms

Fig.3

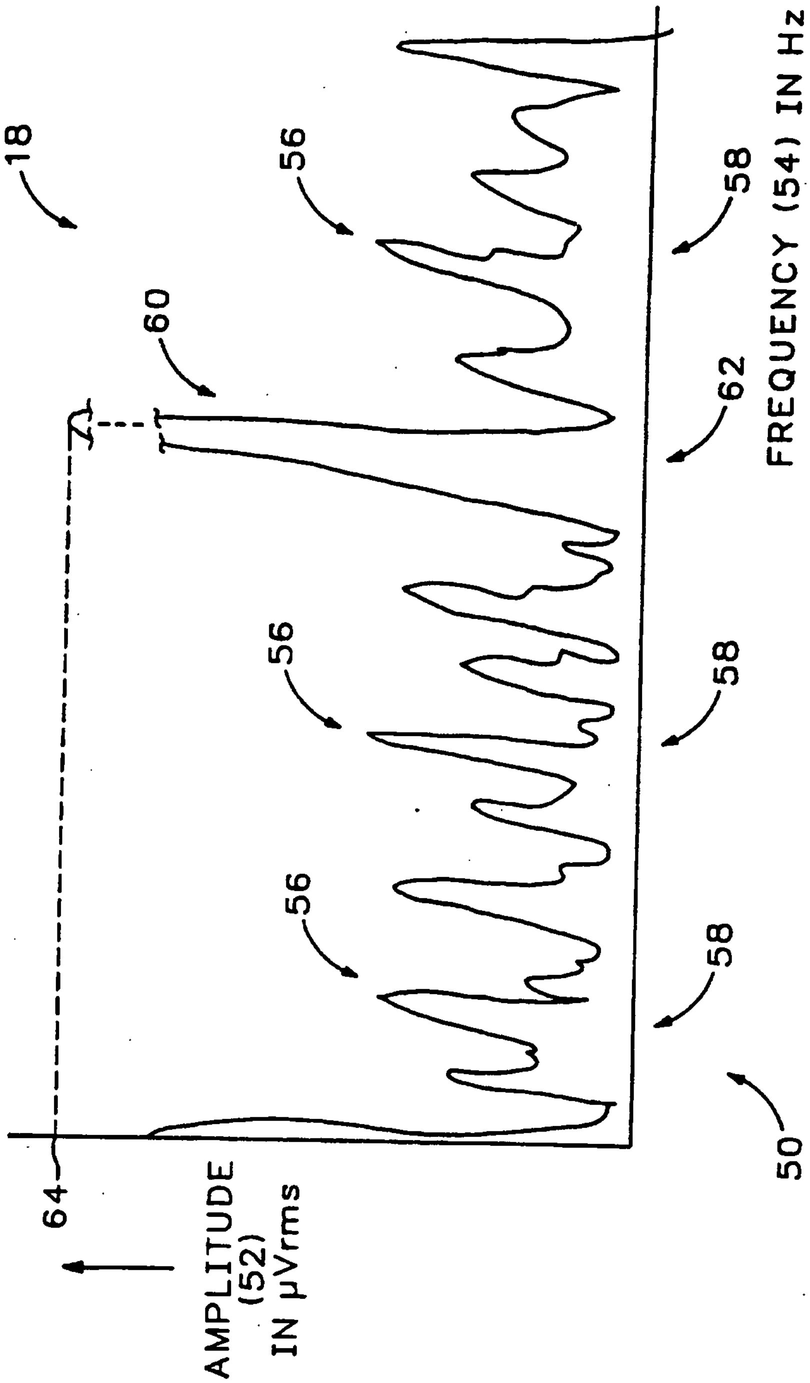

18
56
60
56
56
58
62
58
58
50
64
FREQUENCY (54) IN Hz
AMPLITUDE (52) IN μVrms

Fig.4

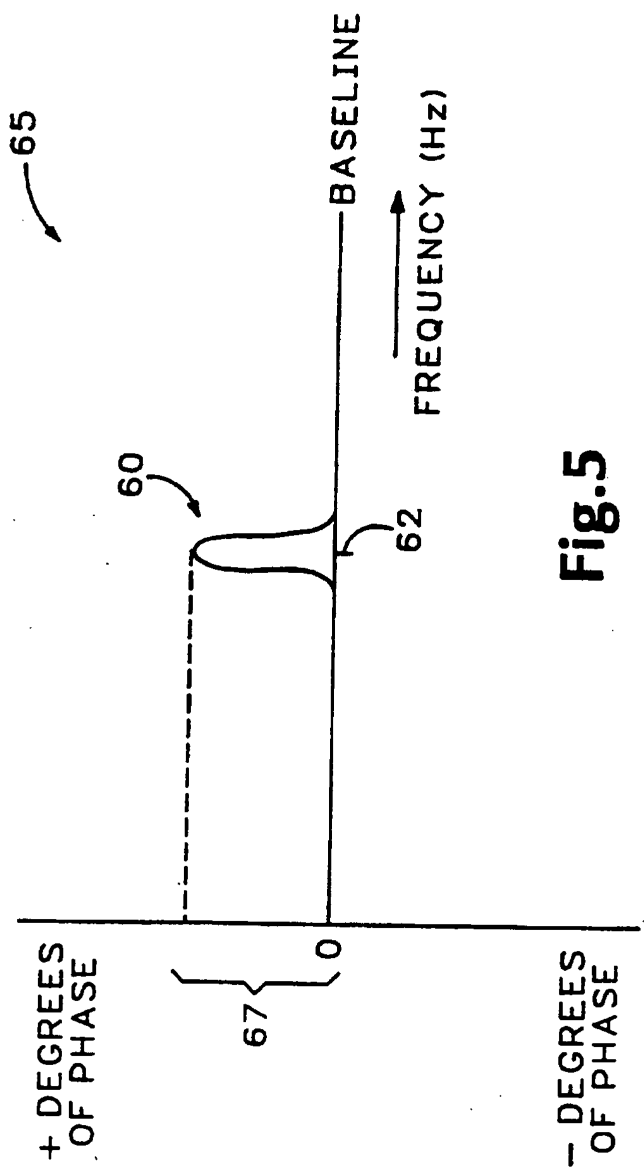

65
BASELINE
FREQUENCY (Hz)
60
62
+ DEGREES OF PHASE
0
67
− DEGREES OF PHASE

Fig.5

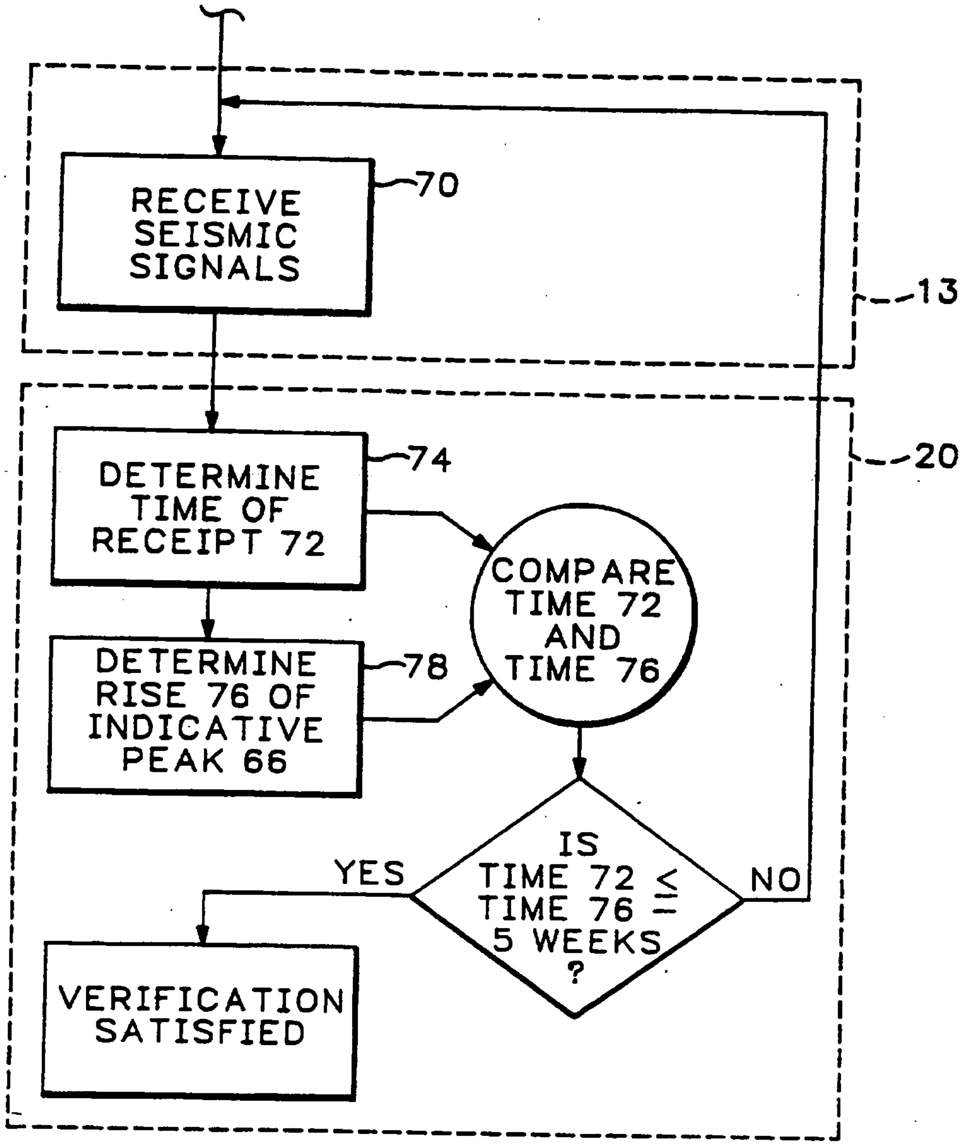

RECEIVE SEISMIC SIGNALS
70
13
DETERMINE TIME OF RECEIPT 72
74
20
COMPARE TIME 72 AND TIME 76
DETERMINE RISE 76 OF INDICATIVE PEAK 66
78
IS TIME 72 ≤ TIME 76 ≦ 5 WEEKS ?
YES
NO
VERIFICATION SATISFIED

Fig.6

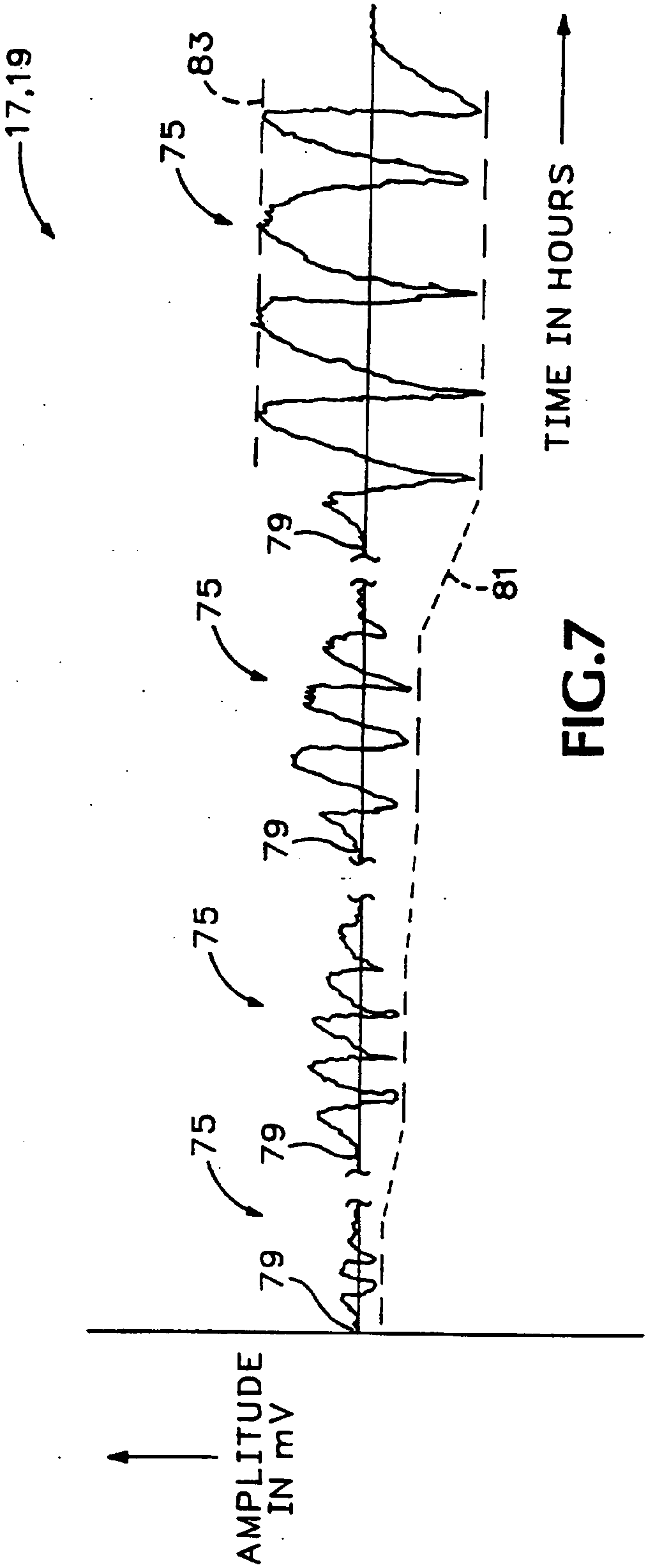


FIG.7

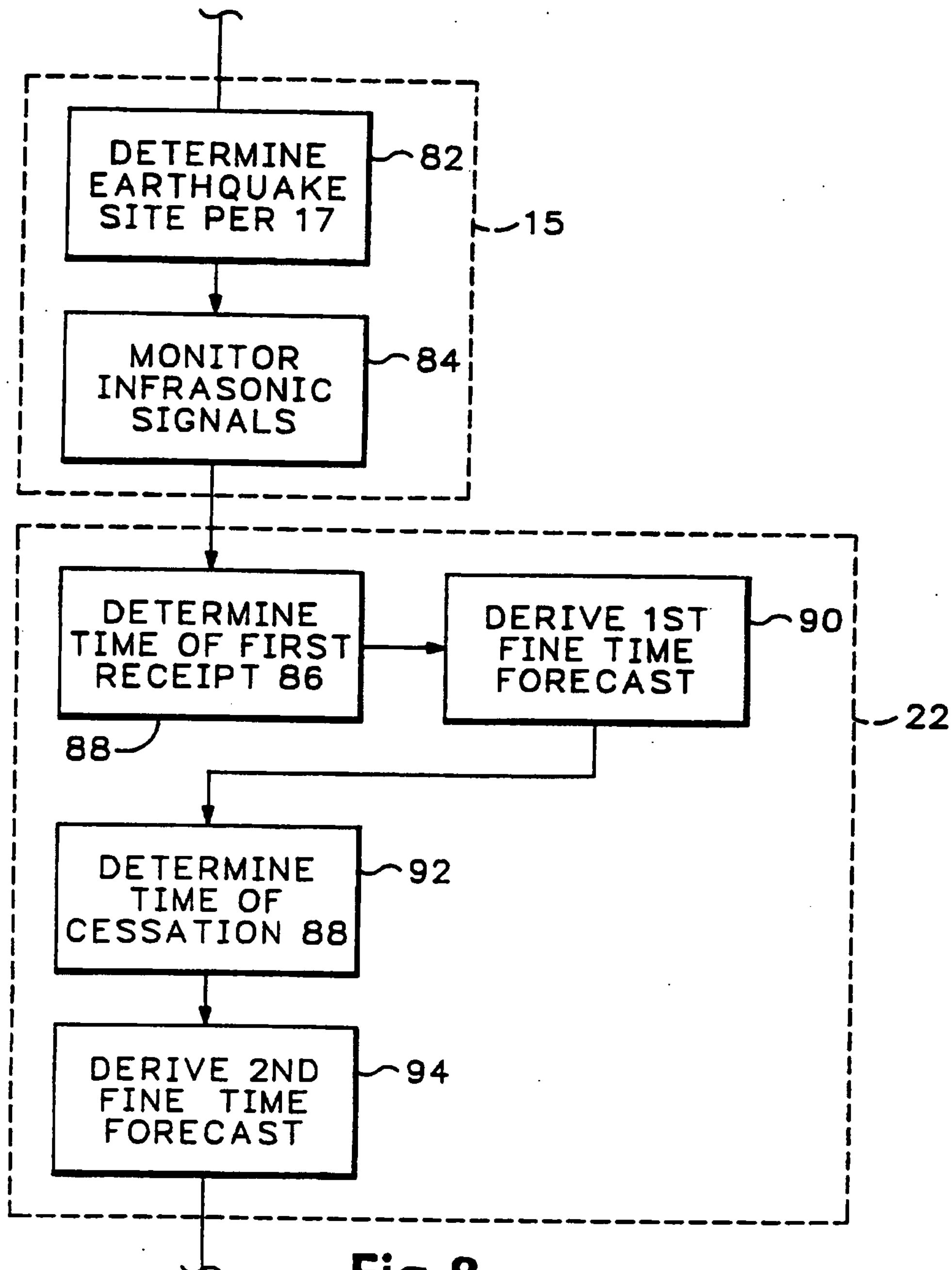

DETERMINE EARTHQUAKE SITE PER 17
82
15
MONITOR INFRASONIC SIGNALS
84
DETERMINE TIME OF FIRST RECEIPT 86
88
DERIVE 1ST FINE TIME FORECAST
90
22
DETERMINE TIME OF CESSATION 88
92
DERIVE 2ND FINE TIME FORECAST
94

Fig.8

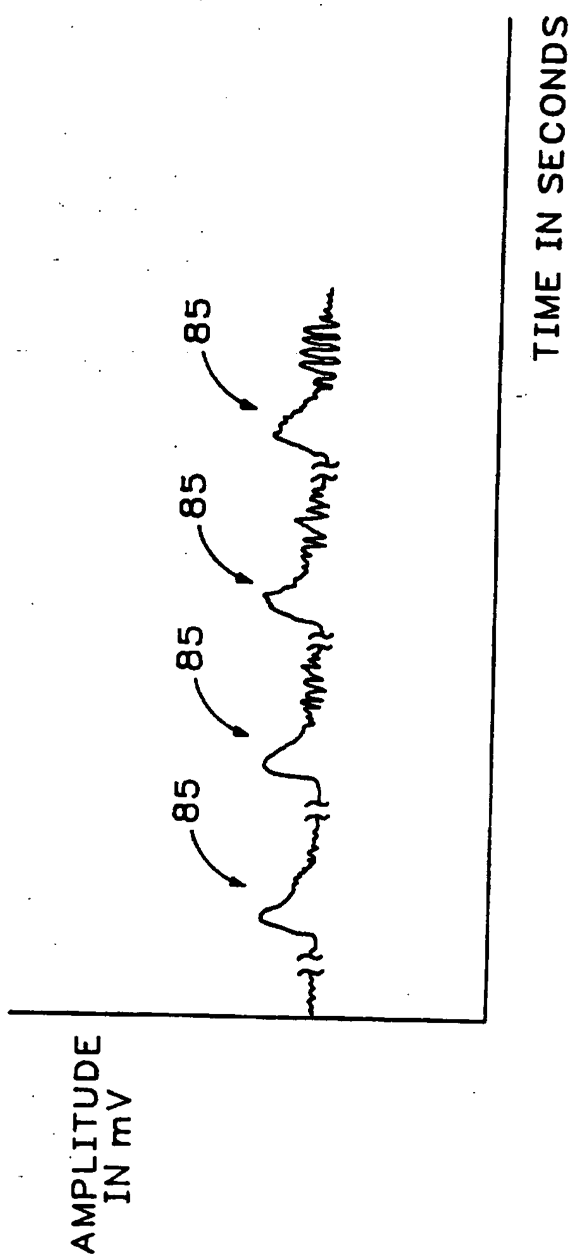


Fig.9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/14052

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :G01V 3/08
US CL. :364/420; 324/344,348,350
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
U.S. : 364/420; 324/344,348,350

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
APS
search terms: earthquake(s) (p) (forecast(ing) or predect(ion, ing, s))

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 4,612,506 (VAROTSOS ET AL.) 16 September 1986, col.1 &2	1-31
X,P	US, A, 5,387,869 (ENOMOTO) 07 February 1995 see Figs. 5A & 5B.	1-3, 7-9, 12, 13, 15, 17, 21, 25, 28, 30 and 31.
Y	US, A, 5,148,110 (HELMS) 15 September 1992, abstract.	3, 30
A	US, A, 4,884,030 (NAVILLE ET AL.) 28 November 1989, abstract.	1-31
Y	US, A, 4,904,943 (TAKAHASHI) 27 February 1990, see col. 5	1-31

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be part of particular relevance
- "E" earlier document published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 FEBRUARY 1995	09 MAY 1995

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	ANDREW F. BODENDORF Joni Hill
Facsimile No. (703) 305-3230	Telephone No. (703) 305-9711

Form PCT/ISA/210 (second sheet)(July 1992)*

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/14052

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 5,187,331 (SAKATA) 16 February 1993, abstact.	1-31
Y	US, A, 4,724,390 (RAUSCHER ET AL.) 09 February 1988, abstract	1-14, 25
Y	US, A, 4,837,582 (TAKAHASHI ET AL.) 06 June 1989, abstract.	1-31
Y	US, A, 5,256,974 (PADDEN) 26 October 1993, cols. 3 and 4	17-31